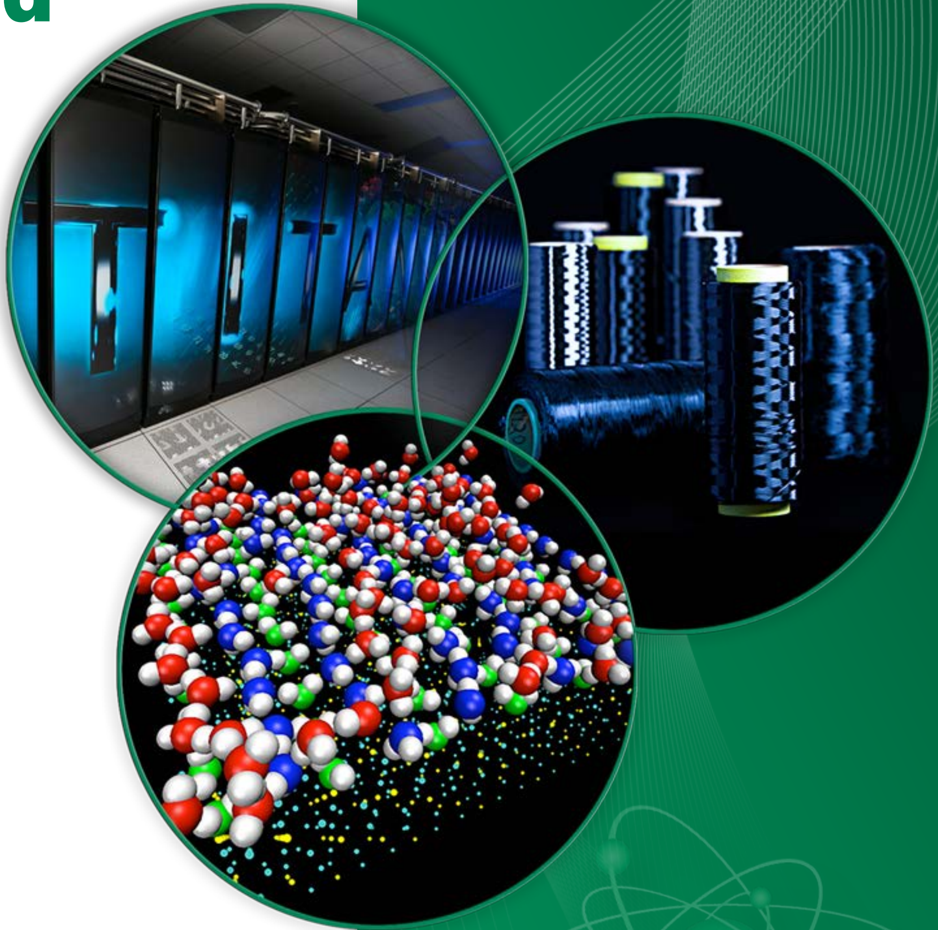
Project ID: LM073

Residual Stress of Bimetallic Joints and Characterization



2014 DOE Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

June 19, 2014

PI: Thomas Watkins; *ORNL*

Donald Erdman III, Gerry Ludtka, Bart Murphy, Adrian Sabau and Sarma Gorti; *ORNL*

Timothy Skszek; *Vehma International*

Xiaoping Niu; *Promatek Research Centre*

Sponsored by

U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Vehicle Technologies Program

Objective: To investigate, develop, characterize bimetallic joint integrity after heat treatment.

Heat treat the aluminum for increased strength and durability while preserving the beneficial as-cast residual stresses

Cosma's bimetallic engine cradle has steel crossmembers with aluminum A356 cast over the tube ends.

Relevance to Vehicle Technologies Goals

- Light-Duty Vehicles: By 2015, develop technologies and a set of options to enable up to 50% reduction in light-duty petroleum-based consumption*
- Lightweighting: By 2015,
  - have an industry lead performer design, build and validate a prototype vehicle that is 50 percent lighter weight compared to a 2002 vehicle.*
  - and validate (to within 10 percent uncertainty) the cost-effective reduction of the weight of passenger vehicle body and chassis systems by 50 percent with recyclability comparable to 2002 vehicles.*

◎ Successful characterization of bi-metallic joints will enable a 20% weight reduction relative to baseline steel assembly

* Vehicle Technologies Program, Multi-Year Program Plan 2011-2015, Dec 2010, pp. 1.0-2, 2.5-2.

Opportunity/Problem Description:
(Why are we investing in this project?)

- *Lightweight, durable and fuel efficient*

Overview

Timeline

- Start: April 28, 2011
- End: Sept 30, 2014
- 85% complete

Budget

- Total Project funding
  - DOE - $1.385M
  - Vehma - $0.515M
- Funding received:
  - FY13 $69k
  - FY14 $82

Barriers*

- Joining characterization ➔ Diffraction methods applied to access joint integrity

Partner

- Vehma International

* Vehicle Technologies Program, Multi-Year Program Plan 2011-2015, Dec. 2010, pp. 2.5-3.

Relevance to barriers

- *Joining*: Development of non-destructive techniques- residual stress characterization of HT joints using diffraction to assess joint integrity and modeling to guide heat treatment. This leads to improved bi-metallic joints further enables the lightweighting technology

Current milestones

- Heat treat schedule for the joint assemblies – complete
- Residual stress determinations – almost complete
- Model development and validation – on track

Approach

Materials identified & provided by Vehma

Vehma
Leak testing:
Conventional heat treat

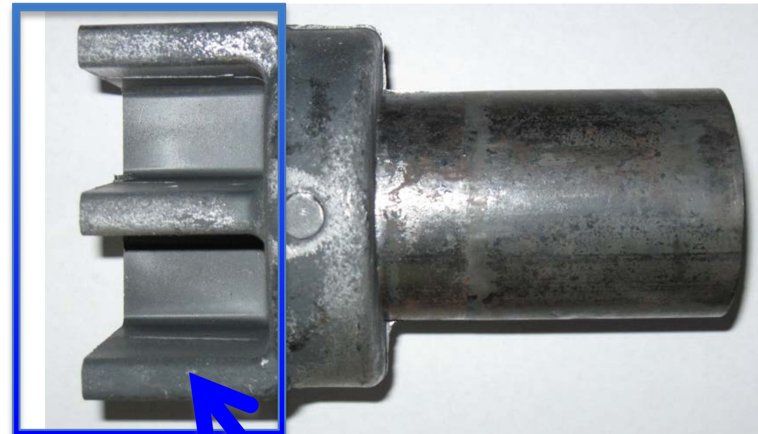
ORNL
IR heat treat,
Neutron residual stress work,
Modeling;
Identify critical heat treat parameters for joint integrity.

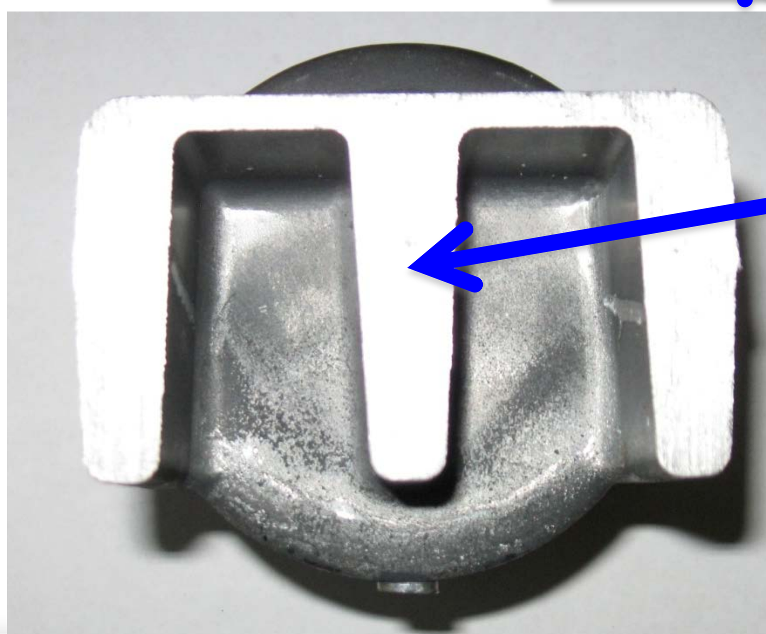
Automotive Community
Understand and model the behavior of residual stresses with heat treatment of cast over AL-steel joints for structural application

Utilizes characterization tools acquired and formerly maintained by the High Temperature Materials Laboratory (HTML) Program at ORNL.

Background: Experimental joints were fabricated for this study

- **A356 aluminum is cast around a steel tube with welded end cap**

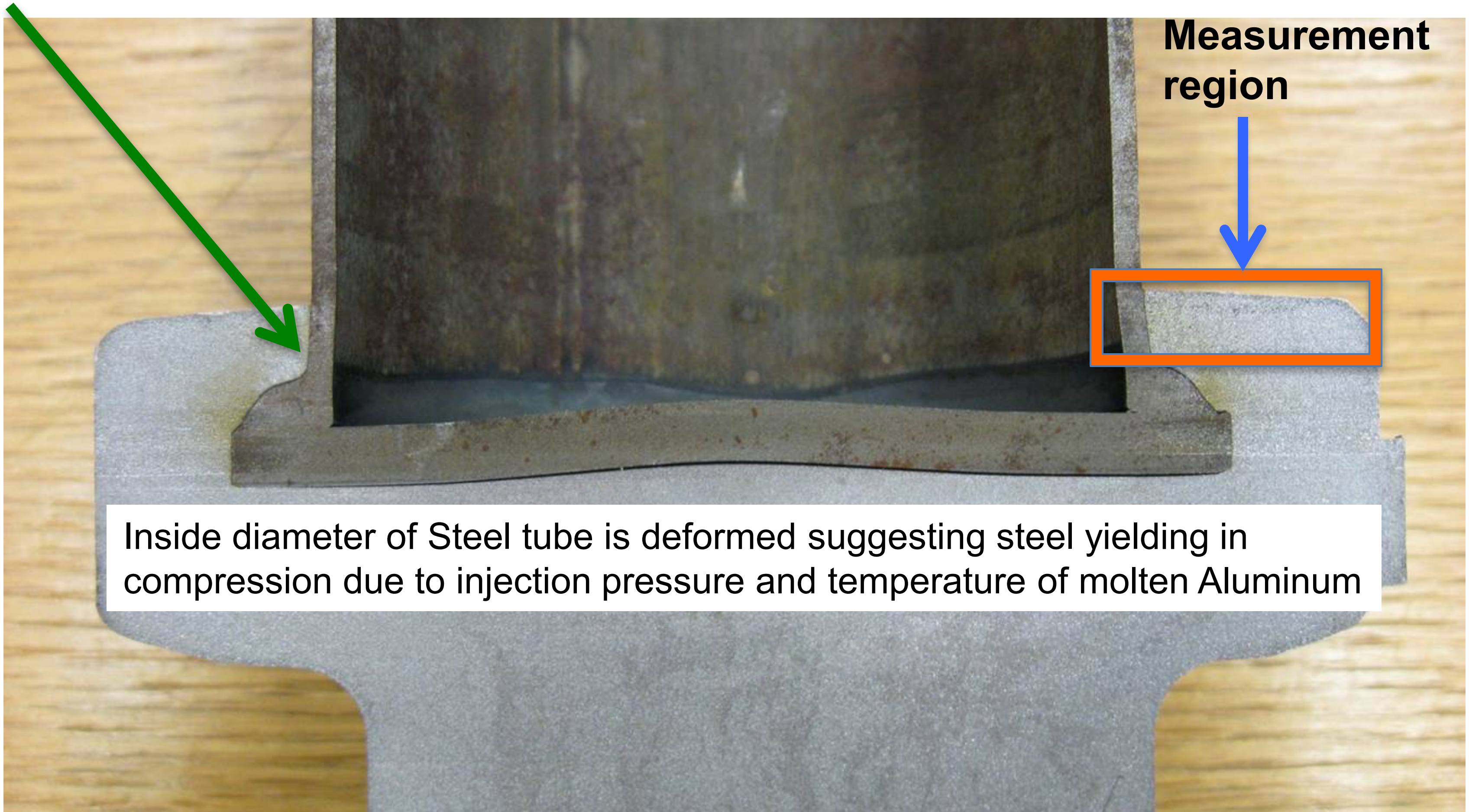




Seek to heat treat 100% AL section only

EDM cut reveals tube with welded end cap and joint cross-section

- Molten Aluminum temperature (600-650°C) will drastically lower the yield strength of the steel*
- Injection pressure of aluminum sufficient to deform steel



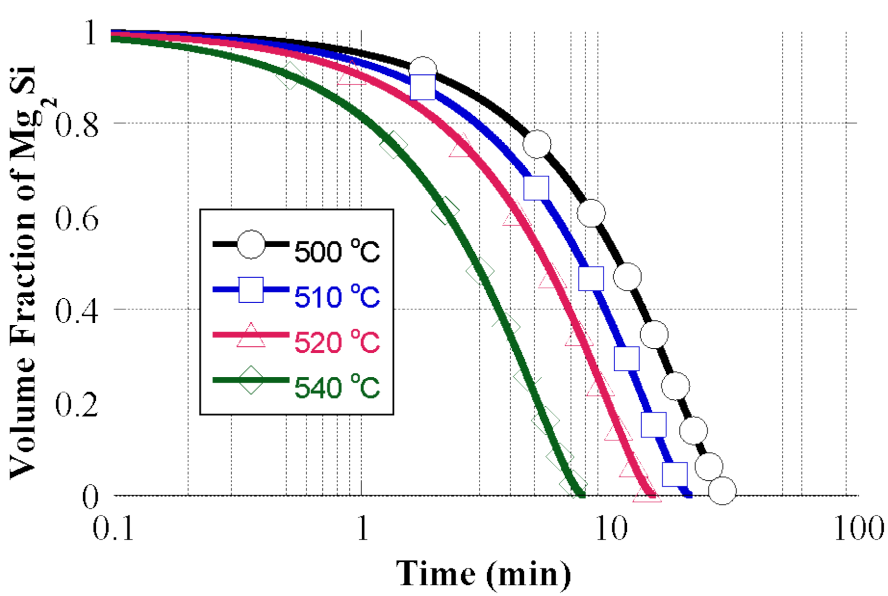
(*NCMS Report, December 1997, Materials Properties Task Team, Oak Ridge, TN.)

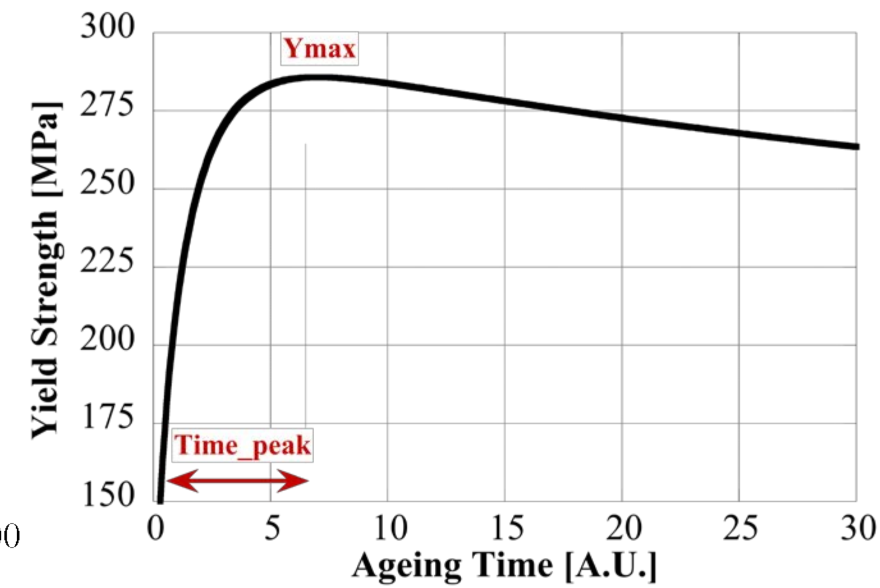
Tech.Acc.: Numerical Simulations were conducted in using models developed in ABAQUS and ProCAST

- Modeling has four components
  - Heat treatments: Phase formation and heat transfer
    - Time and temperatures
    - What phases form and grow
  - Properties
    - Yield strength
    - Young's modulus
    - Thermal expansion
  - Residual stress
    - Cast aluminum
    - Steel tube with welded end cap
  - Casting/solidification process
    - New task, added out of necessity
    - ProCAST
    - Important to residual stress

Tech.Acc.: Phase and property modeling: A semi-empirical model was developed that captures the relationships between the phase fraction and the yield strength of the alloy.

Solutionizing* <<Presently not linked>> Aging**

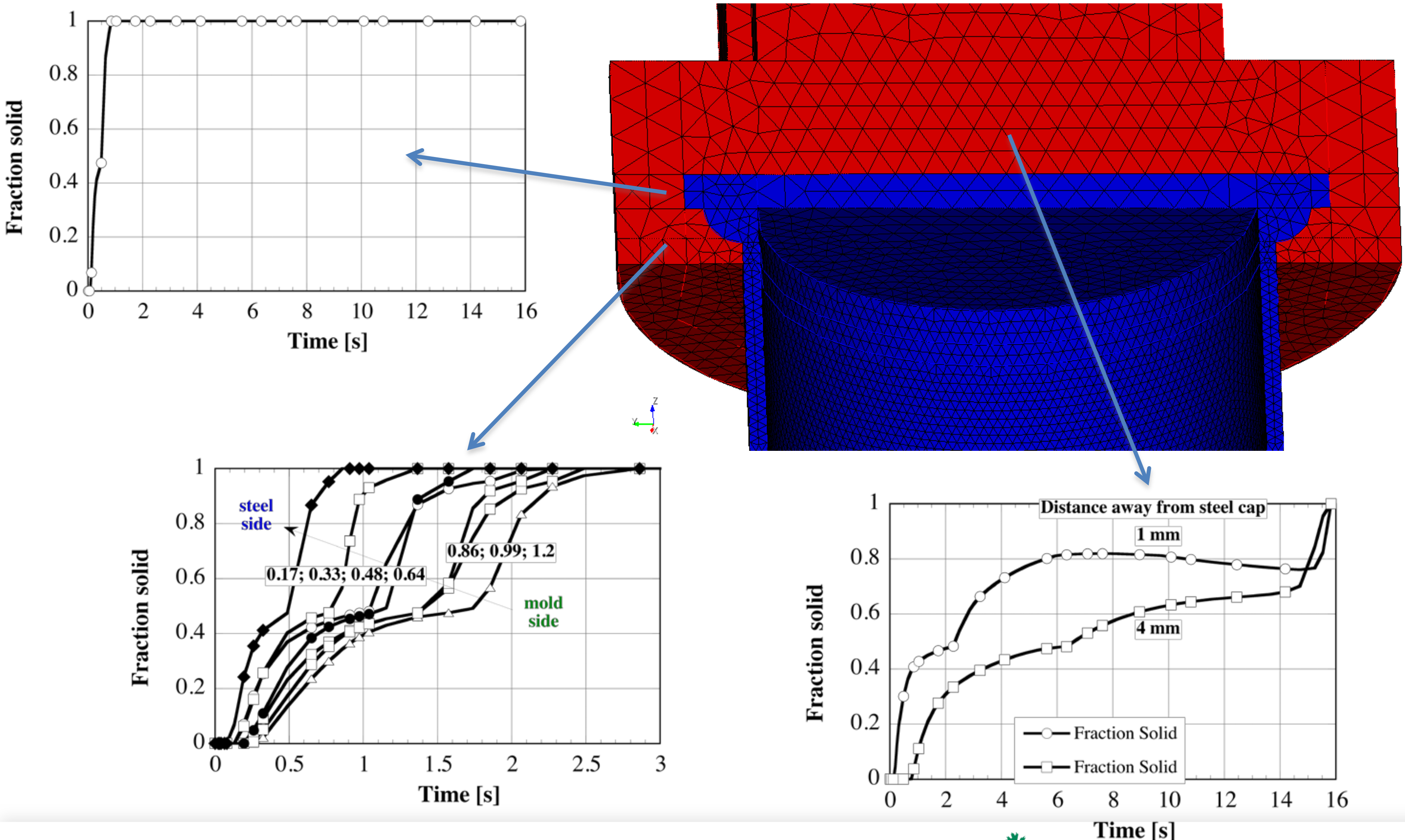




* L.J. Colley. (2011). Microstructure-Property Models for Heat Treatment of A356 Aluminum Alloy, Doctoral dissertation, U. of British Columbia.

** *P.A. Rometsch et al. An age hardening model for Al-7Si-Mg casting alloys. Materials Science and Engineering A 2002, 325, 424-434*

Tech.Acc.: Modeling of solidification is important to the understanding of stress build-up in the joint



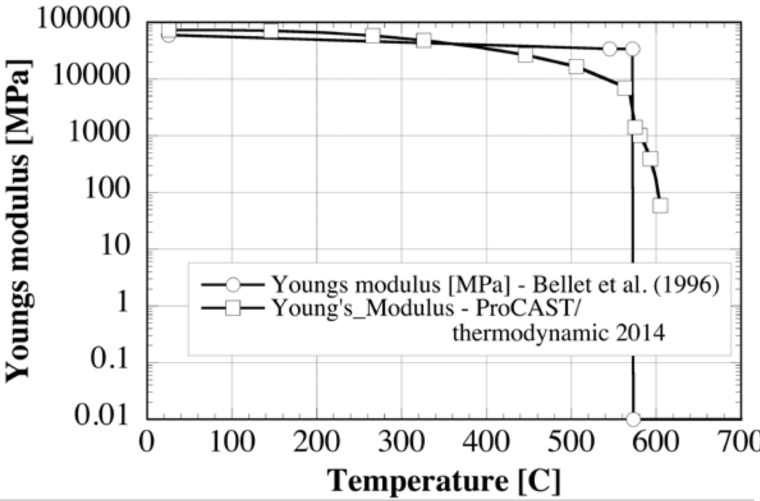
Tech.Acc.: Casting process model: Transition from the fluid dynamics to the solid dynamics was considered to take place at a solid fraction of 30%

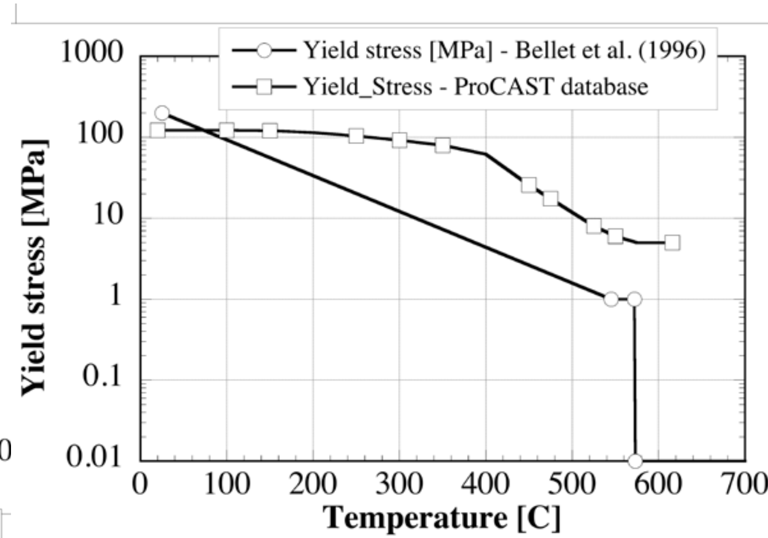
Solidification Domain	*Microstructure*	*Fluid Flow*	*Deformation*
$f_s < f_{ch}$	Floating equiaxed crystals	Mass feeding	N/A (i.e., no yield strength)
$f_{ch} < f_s < f_{pk}$	Dendritic network gets established; Packing increases	Mass feeding reduces, Interdendritic feeding increases	Low yield point increases slowly (0-0.01 MPa)
$f_{pk} < f_s$	Dendritic network	Interdendritic feeding	Yield point increases faster (0.01-0.9 MPa)

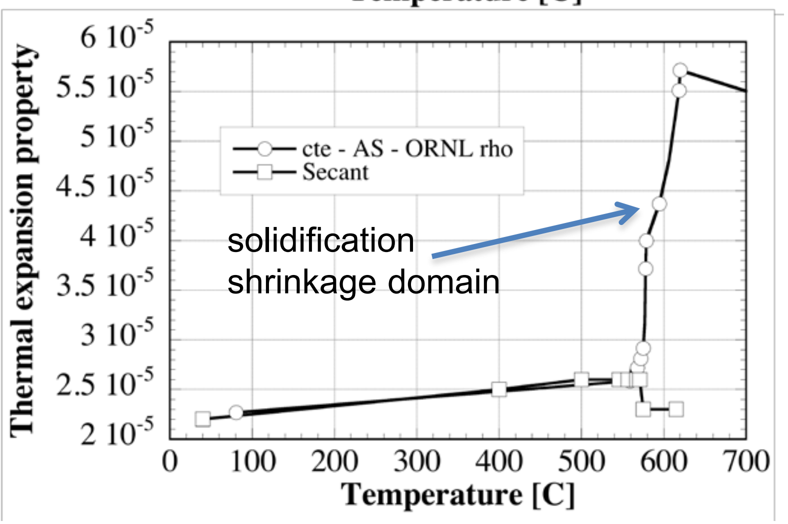
Thermo-mechanical behavior of A356 alloy was that considered by Kim et al. (1991) and Sabau (2006).

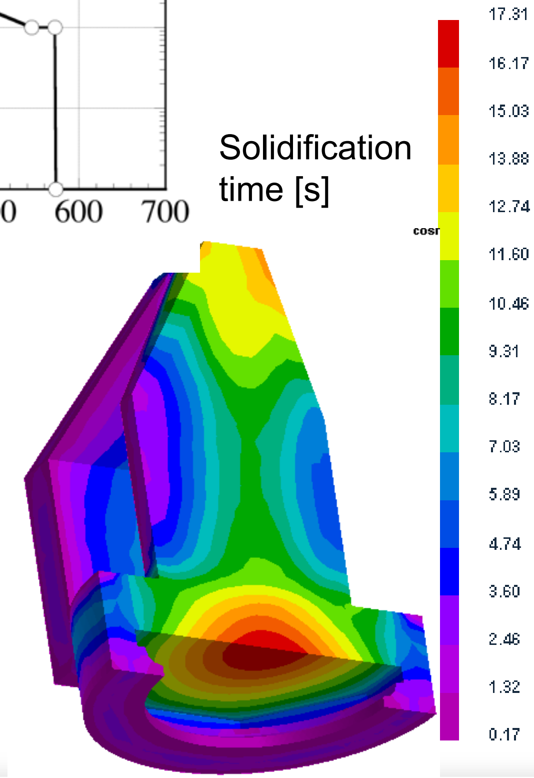
f_s = solid fraction; f_{ch} = coherency fraction (dendrites touching); f_{pk} = packing fraction (when matrix support stress)

Tech.Acc.: Thermo-mechanical properties were calculated using thermodynamic/microstructure modules in ProCAST



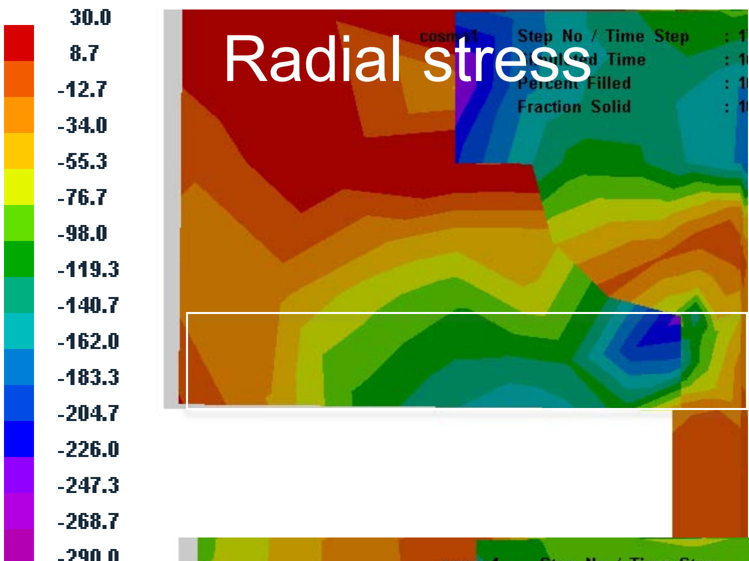


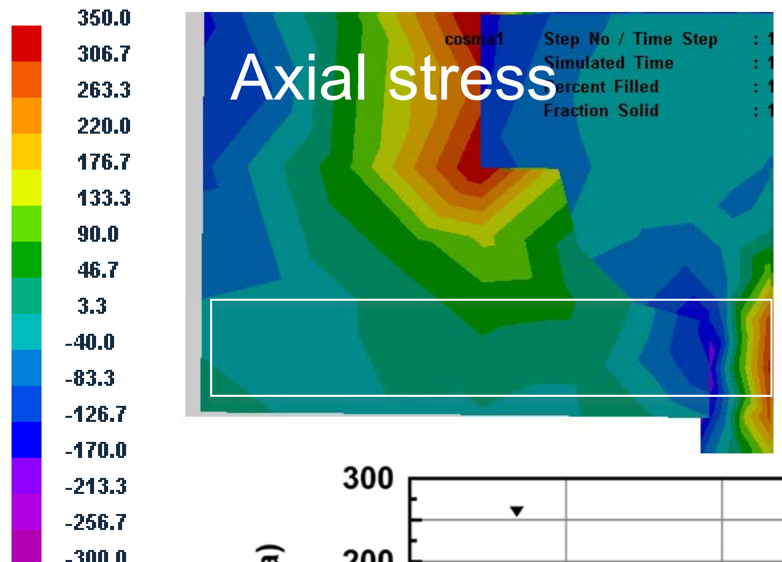


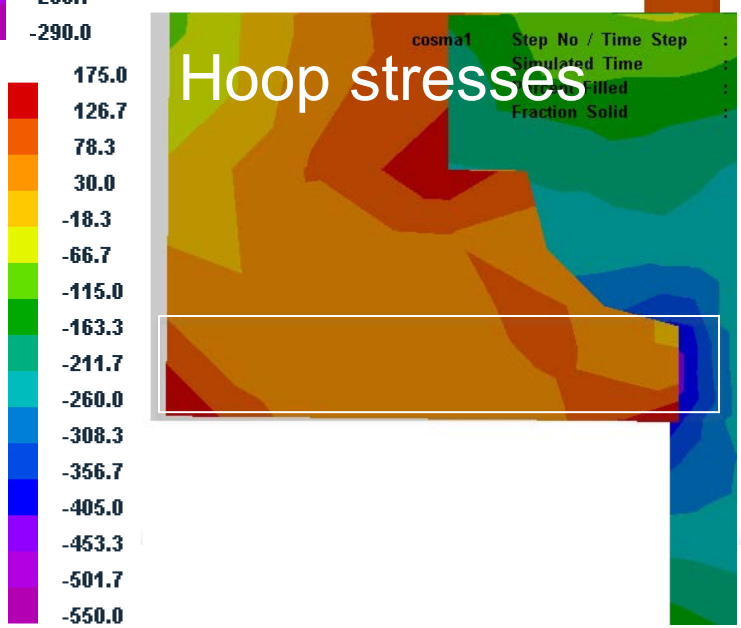


Oak Ridge National Laboratory
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

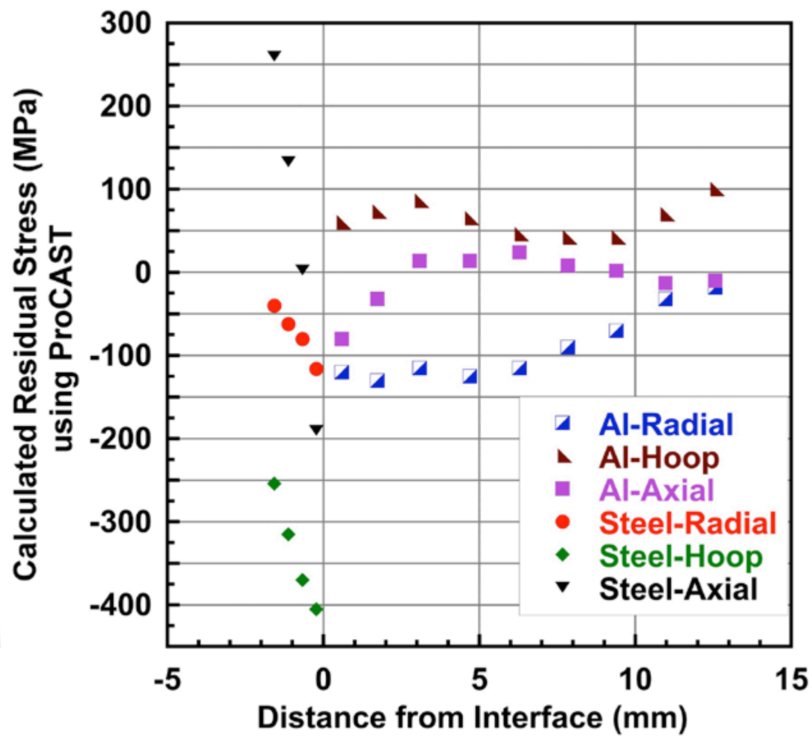
Tech.Acc.: Residual stresses were calculated using ProCAST



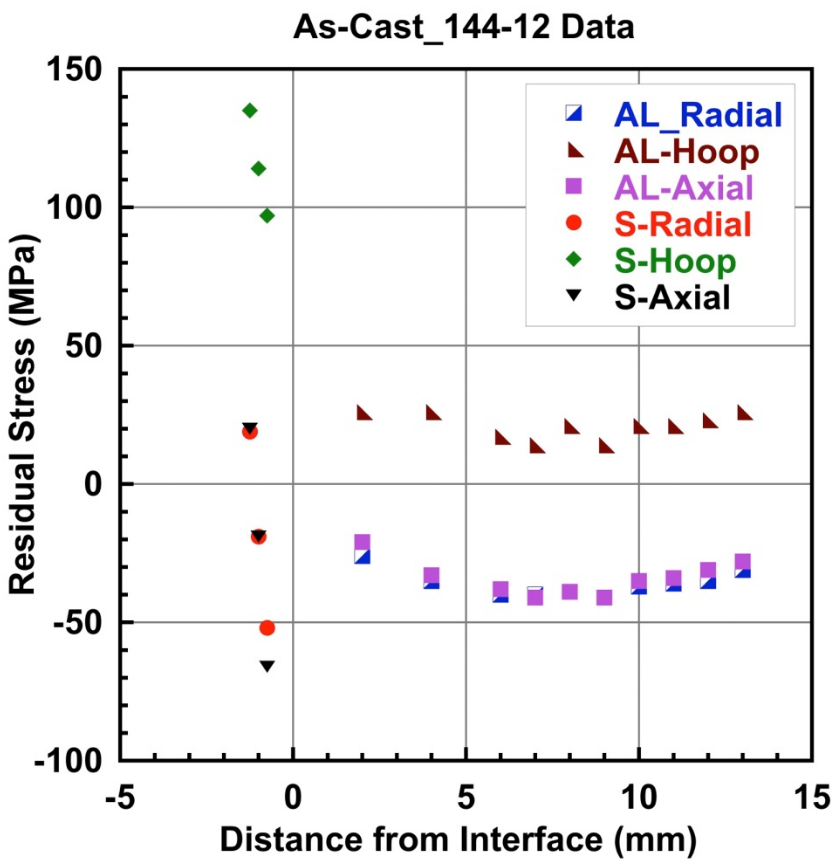


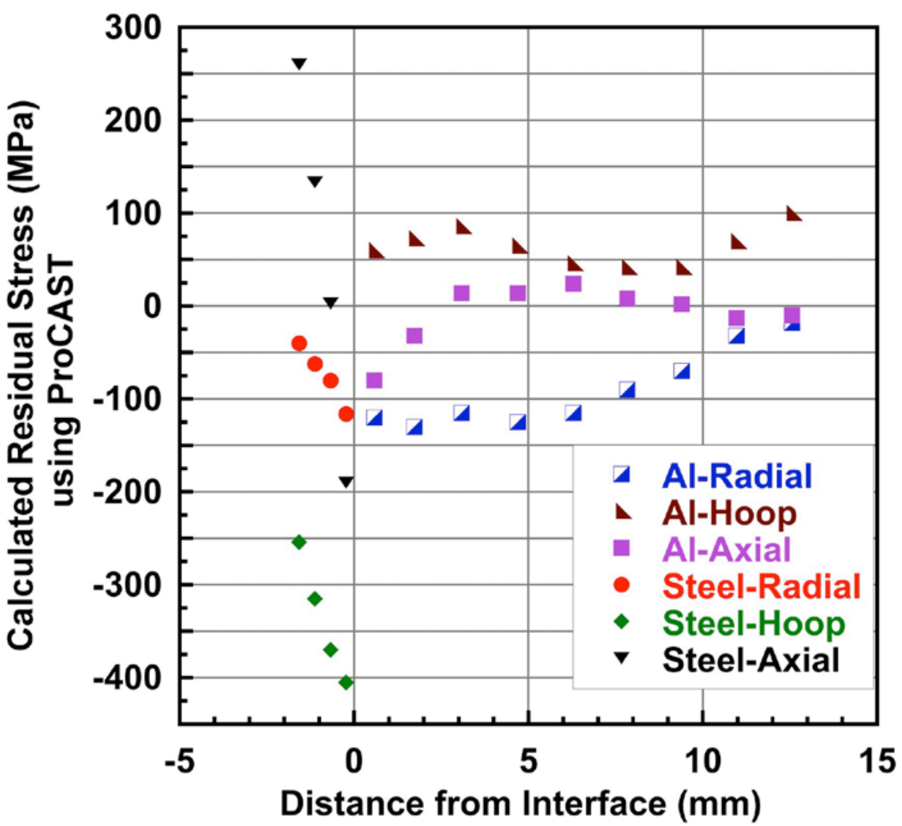


Stress data was obtained through crude averaging of the contour data; more accurate post-processing of the data is required.



Tech.Acc.: Limited agreement between numerical simulation results obtained with ProCAST and measured data; Additional software improvements are needed





Response to Reviewer's comments

There were several compliments and affirmations. Thanks.

The repeated criticisms trended into 3 areas:

1. Limited reporting: This is recognized, but substantial amounts of the information generated has been designated as CRADA protected. As this is a CRADA: "OBLIGATIONS AS TO PROTECTED CRADA INFORMATION

A. Each Party may designate as Protected CRADA Information any Generated Information produced by its employees which meets the definition of Article I.F and, with the agreement of the other Party, so designate any Generated Information produced by the other Party's employees which meets the definition of Article I.F. All such designated Protected CRADA Information shall be appropriately marked. B. For a period of three (3) (not to exceed 5) years from the date Protected CRADA Information is produced, the Parties agree not to further disclose such information…" There are some exceptions which are not germane at this time.

2. No vision or realistic outcome: The vision is to utilize weight saving bi-metallic joints in structural applications for automobiles. In order to do that, preservation of the beneficial residual stresses with heat treating is key. This control couples with a modified T6 heat treatment will facilitate a 20% weight reduction relative to the baseline steel.

3. Corrosion: Corrosion is a concern if the joint loses integrity. The objective here is to preserve the beneficial as-cast residual stresses while heat treating the aluminum "knuckle" for increased strength and durability. IF the beneficial residual stresses are preserved and the joint maintains its integrity, does not crack or delaminate, corrosion will be minimized.

Collaborations and coordinations with other institutions: Partner

- VEHMA INTERNATIONAL (Industry):
  - Vehma's role is to collaborate and guide the work along the most useful path to achieve desired heat treatments and joint integrity
  - Supplies samples
  - Telecons & meetings
  - Exchange of technical information to assist with each others analyses; share experimental results on samples

Future Work

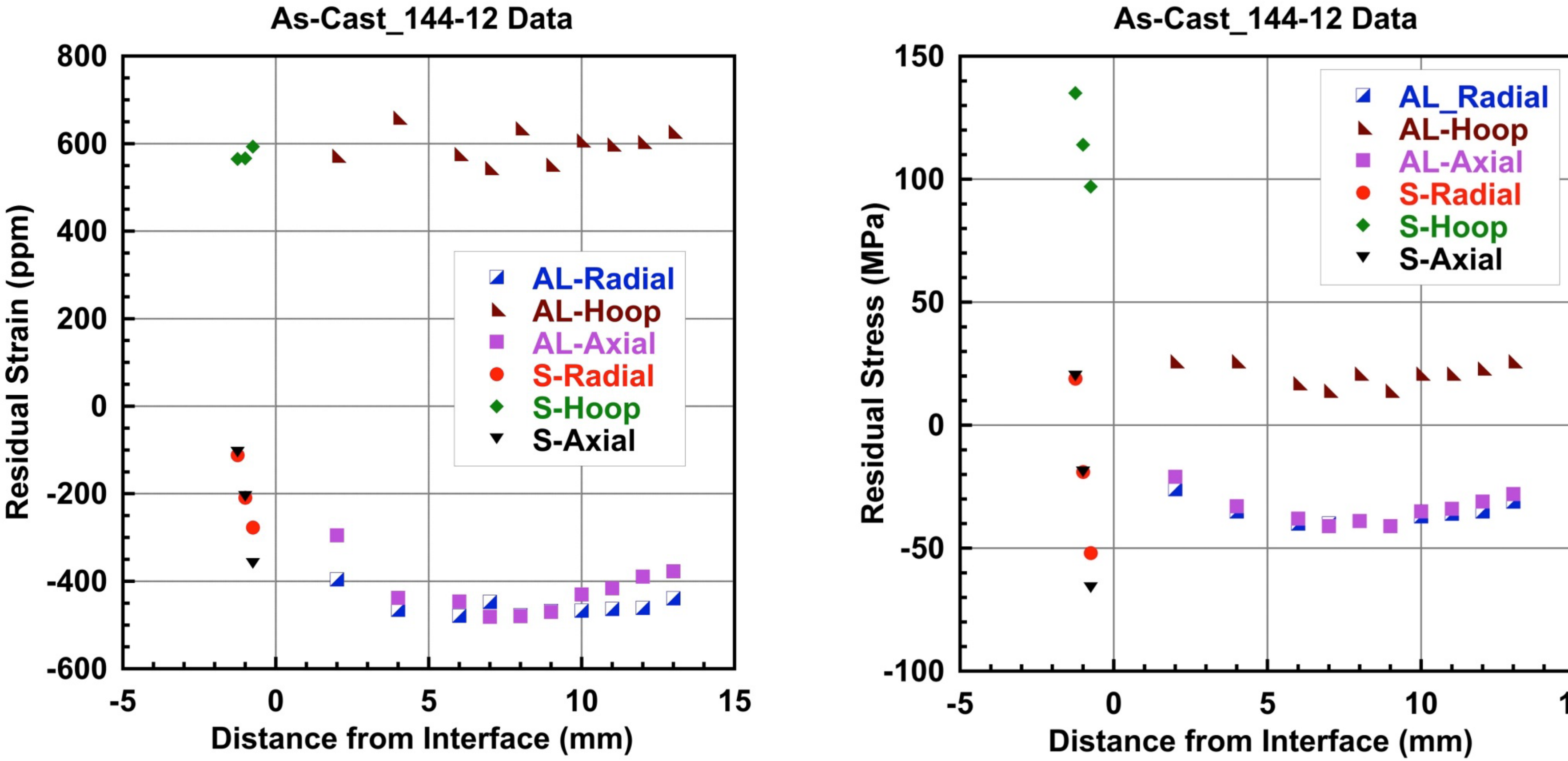
- Report model results using the current-state-of-the art metal casting simulation software
- Assess accuracy for residual stress predictions for squeeze castings
- Finish residual stress determinations

Summary

- **Relevance:** Joints will enable weight reduction in automotive assemblies which helps to meet *Lightweighting & VT goals*
- **Approach/Strategy:**
  - Heat treat joints
  - Characterization of castings and joints: mechanical testing and residual stress (neutrons: unique) to access joint integrity
  - Modeling of process
- **Technical Accomplishments:**
  - Prototype furnace assembled
  - Modeling progressing: Casting process, phase, property, residual stress
- **Collaborations and Coordination with Other Institutions:** Telecons regularly to discuss latest results
- **Proposed Future Work:** Finish model development and joint characterizations; Complete T5 (<12 hrs) and T6 (<3 hrs) treatment schedules for joint-only samples.

Technical Backup slides

Tech.Acc.: As-Cast: Tensile hoop strains in steel observed, but less tensile than bare tube



- Analytical solutions* based on an elastic response to thermal expansion mismatch predict compressive hoop strains in steel
- Hoop tension found in steel, partly due to pre-joined condition and partly due to the deformation from molten aluminum injection

*A.C. Ugural & S.K. Fenster, Advanced Strength and Applied Elasticity, 2003; E. Volterra & J.H. Gaines, Advanced Strength of Materials, 1971.

Tech.Acc.: T5: Tensile hoop strains in steel reduced/more compressive